TACCIMO Literature Report

Literature Report – Annotated Bibliography Format
Report Date: April 1, 2013

Content Selections:
FACTORS – Air Quality
CATEGORIES – ALL
REGIONS – National, East, R9: Eastern, North Atlantic, R8: Southern, South Atlantic, South Central

How to cite the information contained within this report

Each source found within the TACICMO literature report should be cited individually. APA 6th edition formatted citations are given for each source. The use of TACCIMO may be recognized using the following acknowledgement:

"*We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service.*"

Best available scientific information justification

Content in this Literature report is based on peer reviewed literature available and reviewed as of the date of this report. The inclusion of information in TACCIMO is performed following documented methods and criteria designed to ensure scientific credibility. This information reflects a comprehensive literature review process concentrating on focal resources within the geographic areas of interest.

Suggested next steps

TACCIMO provides information to support the initial phase of a more comprehensive and rigorous evaluation of climate change within a broader science assessment and decision support framework. Possible next steps include:

1. Highlighting key sources and excerpts
2. Reviewing primary sources where needed
3. Consulting with local experts
4. Summarizing excerpts within a broader context

More information can be found in the user guide. The section entitled Content Guidance provides a detailed explanation of the purpose, strengths, limitations, and intended applications of the provided information.

Where this document goes

The TACCIMO literature report may be appropriate as an appendix to the main document or may simply be included in the administrative record.

Brief content methods

Content in the Literature Reports is the product of a rigorous literature review process focused on cataloguing sources describing the effects of climate change on natural resources and adaptive management options to use in the face of climate change. Excerpts are selected from the body of the source papers to capture key points, focusing on the results and discussions sections and those results that are most pertinent to land managers and natural resource planners. Both primary effects (e.g., increasing temperatures and changing precipitation patterns) and secondary effects (e.g., impacts of high temperatures on biological communities) are considered. Guidelines and other background information are documented in the user guide. The section entitled Content Production System fully explains methods and criteria for the inclusion of content in TACCIMO.

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Effects by Source

Monday, April 01, 2013

RESOURCE AREA (FACTOR): AIR QUALITY

ACID DEPOSITION

NATIONAL

Bytnerowicz, A., Omasa, K., & Paoletti, E. (2007). Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. Environmental Pollution, 147, 438-445.

"Higher temperatures, changed precipitation patterns and modified net primary production (NPP) increase the weathering rate, resulting in higher critical loads (i.e., lower sensitivity of ecosystems to APs [air pollutants]) (Posch, 2002). The increased mineralization increases N [nitrogen]availability and leaching (Mol-Dijkstra and Kros, 2001). Deposition of various APs [air pollutants] also increases N availability. Climate change acts to worsen the problem of acidification by increasing the production - and deposition to soils - of HNO3 from NO, and the proportion of NH3 converted into ammonium sulfate, which in turn may result in further acidification of soils (Sanderson et al., 2006). "

"Since N [nitrogen] often is the limiting nutrient in forests, N deposition may increase wood production and accumulation of soil organic matter, thus increasing C sequestration into the forest. Earlier estimates suggested that this mechanism could take up one third of the global CO2 emission from fossil fuel if most of the N deposition was taken up by trees and used to form new woody biomass (Holland et al., 1997). Recent data, however, suggest that the increase in N deposition may cause a 10-times smaller additional CO2 sequestration in forests (Nadelhoffer et al., 1999). When the large uptake is mainly due to elevated growth, it is likely that this is a transitory phenomenon, whereas it could be a C [carbon] sink for a long period if soil accumulation is the main cause since below ground C has much lower turnover times than above ground C."

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Crosby, B. J., Dunscomb, J. K., . . . Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the Eastern United States. Annals of the New York Academy of Sciences, 1162, 99-135.

"In the United States, there is little evidence for increased tree growth from the fertilizing effect of this added N [Nitrogen], probably because most of the N appears to be retained in the soil organic matter where it is unavailable to the plants (Nadelhoffer et al. 1999; Templer et al. 2005)."

Mohan, J. E., Cox, R. M., and Iverson, L. R. (2009). Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. Canadian Journal of Forest Research, 39, 213-230. doi:10.1139/X08-185

"Computations have indicated that 10.1% of the global natural terrestrial ecosystems is exposed to N deposition above the critical load of 1 g•m–2•year–1, and this area will increase to 25% by 2030 under the Intergovernmental Panel on Climate Change’s Special Report on Emissions Scenarios A2 scenario of emission reductions (Dentener et al. 2006)."

Payne, R. J., Dise, N. B., Stevens, C. J., Gowing, D. J., Duprи, C., Dorland, E., ... & Muller, S. (2013). Impact of nitrogen deposition at the species level. Proceedings of the National Academy of Sciences, 110(3), 984-987. doi:10.1073/pnas.1214299109

"Our analysis [of nitrogen deposition in European grasslands] identifies many more changes in the community below the critical load than above it. Thus, a long-term incremental increase in N deposition would have a greater impact in a site with a current loading of 10 kgNha−1 y−1 than a site with a current loading of 30 kg N ha−1 y−1. This finding highlights the importance of protecting currently unpolluted areas from new pollution sources: we cannot rule out ecological impacts from even relatively small increases in reactive N deposition in these areas. It also suggests that less overall ecological damage may result from new sources of reactive N in current high-N deposition regions, where a shift to a more pollution-tolerant community may have already occurred, rather than regions that currently receive low levels of pollution and are sensitive to even small increases in N deposition."

Ryan, M., Archer, S., Birdsey, R., Dahm, C., Heath, L., Hicke, J. ., . . . Schlesinger, W. (2008). Land resources. in: The effects of climate change on agriculture, land resources, water resources, and biodiversity. a report by the U.S. climate change science program and the subcommittee on global change research. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 362.

"There is evidence that chronic nitrogen deposition also increases carbon storage in surface soil over large areas (Pregitzer et al. 2008)."

"Chronic nitrogen inputs over many years could lead to nitrogen saturation (a point where the system can no longer use or store nitrogen), a reduction in forest growth, and increased levels of nitrate in streams (Aber et al. 1998; Magill et al. 2004), but observations of forest ecosystems under natural conditions have not detected this effect (Magnani et al. 2007)."

"Experiments and field studies have shown that the positive effect of elevated CO2 on productivity and carbon storage can be constrained by low nitrogen availability, but in many cases elevated CO2 causes an increase in nitrogen uptake (Finzi et al. 2006; Johnson 2006; Luo et al. 2006; Reich et al. 2006)."

"For nitrogen-limited ecosystems, increased nitrogen availability from nitrogen deposition enhances the productivity increase from elevated CO2 (Oren et al. 2001) and the positive effects of changes in temperature and precipitation."

"Overall, there is strong evidence that the effects of nitrogen deposition on forest growth and carbon storage are positive and might exceed those of elevated CO2 (Körner 2000; Magnani et al. 2007)."

R9: EASTERN

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Crosby, B. J., Dunscomb, J. K., . . . Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the Eastern United States. Annals of the New York Academy of Sciences, 1162, 99-135.

"Nitrogen accumulation may also lead to a condition known as N saturation, in which overabundance of this key nutrient results in a series of impacts on microbial and plant production and N cycling (e.g., Aber et al. 1998)."

"Deposition loads in eastern alpine zones probably range from 10 to 20 kg N/ha-y (Ollinger et al. 1993; Weathers et al. 2000), and have probably been at that level for several decades, so it is possible that productivity and species shifts have already occurred in these ecosystems."

"Bogs and fens are listed by Bobbink et al. (1998) as being among the ecosystems at highest risk of species compositional shifts due to N [Nitrogen] deposition."

"In the last 20 years, however, research has shown that chronic N [Nitrogen] addition can have toxic effects that alter plant, soil, and microbial interactions, and can lead to loss of soil fertility, reduced productivity, and even tree death. The basic processes involved have been organized in a conceptual framework referred to as "nitrogen saturation" (e.g., Aber et al. 1998)."

"Herbivorous insects tend to prefer plants with higher N [Nitrogen] concentration, and there is some evidence that increased N may be predisposing trees to attack by insect pests such as the hemlock woolly adelgid (Adelges tsugae) (e.g., McClure 1991) and the beech scale (Cryptococcus fagisuga) (Latty et al. 2003). Increased susceptibility to pests could be a serious liability for eastern forests, given the number of exotic insect pests that are being introduced continually through enhanced global trade (Lovett et al. 2006)."

Ryan, M., Archer, S., Birdsey, R., Dahm, C., Heath, L., Hicke, J. ., . . . Schlesinger, W. (2008). Land resources. in: The effects of climate change on agriculture, land resources, water resources, and biodiversity. a report by the U.S. climate change science program and the subcommittee on global change research. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 362.

"Nitrogen deposition in the eastern United States and California can exceed 10 kg N [Nitrogen] ha-1 yr-1 and likely has increased 10-20 times above pre-industrial levels (Galloway et al. 2004). Forests are generally limited by nitrogen availability, and fertilization studies show that this increased deposition will enhance forest growth and carbon storage in wood (Gower et al. 1992; Albaugh et al. 1998; Adams et al. 2005)"

NORTH ATLANTIC

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Crosby, B. J., Dunscomb, J. K., . . . Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the Eastern United States. Annals of the New York Academy of Sciences, 1162, 99-135.

"In three cases, a high-elevation spruce–fir forest on Mt. Ascutney, Vermont, a red pine forest in central Massachusetts, and a mixed-oak forest in southern New York, the N [Nitrogen] addition resulted in declines in productivity and increases in tree mortality (McNulty et al. 1996; Magill et al. 1997; Wallace et al. 2007). The mechanism of this effect is not yet understood, but in all three cases soil acidification and the resulting aluminum toxicity to roots is a strong possibility (Aber et al. 1998; Wallace et al. 2007)."

Ollinger, S. V., Goodale, C. L., Hayhoe, K., & Jenkins, J. P. (2008). Potential effects of climate change and rising CO2 on ecosystem processes in northeastern U.S. forests. Mitigation and Adaptation Strategies for Global Change, 13, 467-485. doi: 10.1007/s11027-007-9128-z

"Under the four climate scenario simulations that included CO2 growth enhancement effects, mean predicted N losses for 2070–2099 increased slightly in the four deciduous stands [in New York, Massachusetts, and New Hampshire]—to between 21% and 46% of N deposition inputs—whereas N losses at Howland [Maine] increased to more than twice the input from deposition (Fig. 6, Table 6…). These increases in N loss occurred despite increased plant demand for N by more quickly growing trees, indicating that plant demand for N did not keep pace with increased N availability from accumulated N deposition and from faster N mineralization associated with increasing temperature."

"Under climate change scenarios that lacked CO2 enhancement effects, mean N losses for the 2070–2099 period increased more markedly and ranged from 57% of atmospheric inputs at Harvard Forest [Massachusetts] to over three times the atmospheric inputs at Howland [Maine] (Fig. 6). These higher N loss values stem from the lower plant demand for N that occurs in the absence of CO2 fertilization."

SOUTH ATLANTIC

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Elevated nitrogen deposition downwind of large, expanding metropolitan centers or large agricultural operations has been shown to affect forests when nitrogen deposited is in excess of biological demand (nitrogen saturation). Across the southern United States it is largely confined to high elevations of the Appalachian Mountains (Johnson and Lindberg, 1992), although recent increases in both hog and chicken production operations have caused localized nitrogen saturation in the Piedmont and Coastal Plain (McNulty et al., forthcoming)."

EAST

Civerolo, K. L., Hogrefe, C., Lynn, B., Rosenzweig, C., Goldberg, R., Rosenthal, J., … & Kinney, P. L. (2008). Simulated effects of climate change on summertime nitrogen deposition in the eastern US. Atmospheric Environment, 42, 2074–2082. doi:10.1016/j.atmosenv.2007.11.049

"On a percentage basis, the smallest increases in wet N deposition occurred over the Great Lakes region (~3%) and Casco Bay (~9%). These two watersheds actually exhibited decreases in average summertime precipitation, by ~3% and 7%, respectively. The other seven watersheds exhibited increases in wet N deposition by ~10–25% and increases in precipitation by ~6–18%."

"Total N deposition, then, increased by about 3–14% across these [eastern US] watersheds in the simulation driven by the future regional climate fields under the A2 greenhouse gas scenario for the 2050s."

"In the simulations using the A2 regional climate fields for the 2050s, wet N deposition is predicted to increase, primarily as a result of higher precipitation, while dry N deposition is predicted to increase as a result of higher temperatures, leading to a shift from pNO3 to HNO3."

Dietze, M. C., & Moorcroft, P. R. (2011). Tree mortality in the eastern and central United States: patterns and drivers. Global Change Biology, 17, 3312-3326. doi: 10.1111/j.1365-2486.2011.02477.x

"By contrast, the impacts of nitrogen deposition were almost as strong, but caused a decline in mortality, suggesting that the fertilization effects of NO3- are currently stronger than the negative impacts of acidification of NO3- . While not captured by the fitted model, there is some suggestion that at very high levels of deposition mortality begins to increase again (full set of covariate by PFT [plant functional types] plots provided in Supporting Information)."

GENERAL IMPACTS

NATIONAL

Bedsworth, L. (2011). Air quality planning in California's changing climate. Climatic Change, DOI 10.1007/s10584-011-0244-0, 1-18.

"Analysis of the effects of climate change on air pollution have shown that climate change is likely to lead to an increase in the severity and duration of air pollution episodes (Mickley 2007; Mickley et al. 2004). Air pollution levels can be affected by several direct and indirect effects of climate change: (i) increased temperature, (ii) changes in biogenic emissions (e.g., emissions from vegetation), (iii) changes in chemical reaction rates, (iv) changes in atmospheric conditions that affect pollutant mixing, and (v) changes in the atmospheric flows that affect pollutant transport (Hogrefe et al. 2004). In addition, behavioral responses to climate change could result in an increase in emissions, for instance through increased energy demand during heatwaves (Franco and Sanstad 2008; Miller et al. 2008)."

Bytnerowicz, A., Omasa, K., & Paoletti, E. (2007). Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. Environmental Pollution, 147, 438-445.

"The impacts on forest ecosystems have been traditionally treated separately for air pollution and climate change. However, the combined effects of numerous climate change and air pollution factors may significantly differ from a sum of separate effects due to an array of various synergistic or antagonistic interactions. The net effect varies for different ecosystem types and geographic regions, and depends on magnitude of climate or AP drivers, and types of interactions between them (Bazzaz and Sombroek, 1996)."

"Climate change may affect distribution patterns and mixture of APs [air pollutants]. Such changes are caused by changing wind patterns, and amount and intensity of precipitation. The intensity of precipitation determines the atmospheric concentration and deposition of acidifying compounds. This may also change frequency and extent of pollution episodes (e.g., O3)."

"Climate change parameters that trigger stomata opening (e.g., increasing temperature) increase the sensitivity of plants to APs [air pollutants] like SO2 and O3. Parameters that lead to stomata closure (e.g., water stress, increased CO2) help to protect the plant from APs. A complication is that O3 slows the stomatal response to reduced water availability (Paoletti, 2005). Climate change parameters that lead to a longer growing season (e.g., warming) increase the exposure of plants to APs like SO2 and O3, whereas parameters that shorten the growing season (e.g., water stress) reduce the exposure and damage (Guardans, 2002). A simulation for Norway spruce and European beech showed that climate change sensitivity increases in boreal areas and decreases in temperate areas due to temperature and water stress (Guardans, 2002)."

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43, 52-63. doi:10.1016/j.atmosenv.2008.09.051

"Changes in climate affect air quality by perturbing ventilation rates (wind speed, mixing depth, convection, frontal passages), precipitation scavenging, dry deposition, chemical production and loss rates, natural emissions, and background concentrations."

Mickley, L. J. (2007). A future short of breath? Possible effects of climate change on smog. Environment, 49 (6), 35-43.

"The short answer is, as surface temperatures rise, the rates of photochemical reactions that lead to smog formation will accelerate. In addition, trees will also emit greater quantities of VOCs [volatile organic compounds] at higher temperatures, further enhancing concentrations of ozone and secondary organic aerosol."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"In addition to the many abiotic factors that can influence contaminant behavior, altered species migration patterns linked to climate change could be an important factor modulating the transport of POPs [persistent organic pollutants] (Blais et al., 2007). Migratory species, particularly fish, birds, and marine mammals, may be exposed to contaminants in one location and transport these contaminants in substantial quantities to other locations. This biotic transport of contaminants may be similar in magnitude to atmospheric and oceanic transport (Burek et al., 2008). There is evidence, for example, that Arctic and Antarctic birds may act as vectors transporting persistent contaminants from oceans to terrestrial systems via their guano (Blais et al., 2005)."

"Like the POPs [persistent organic pollutants], climate change will influence the environmental fate and behavior of pesticides by altering fundamental mechanisms of environmental partitioning primarily through mechanisms of increased volatility, wet deposition, and enhanced degradation."

NORTH ATLANTIC

Kunkel, K. E., Huang, F.-C., Liang, H.-Z., Lin, J.-T., Wuebbles, D., Tao, Z., Williams, A. , … & Hayhoe, K. (2008). Sensitivity of future ozone concentrations in the northeast USA to regional climate change. Mitigation and Adaptation Strategies for Global Change, 13, 597-606. doi: 10.1007/s11027-007-9137-y

"Figure 3 shows the fractional changes (expressed as percentage of future emissions relative to the present emissions) of biogenic emissions due to the changes in the future climate (2090s). The increases of isoprene emissions ranged from 13 to 57% (from the low to the high scenarios). The relative isoprene emission increases are consistent with the temperature increases because isoprene emissions by vegetation are a function of temperature and incident solar radiation (Guenther et al. 1994, 1995)."

EAST

Dietze, M. C., & Moorcroft, P. R. (2011). Tree mortality in the eastern and central United States: patterns and drivers. Global Change Biology, 17, 3312-3326. doi: 10.1111/j.1365-2486.2011.02477.x

"The most striking result of this analysis is the unexpectedly large role of atmospheric pollutants on the mortality rates of eastern forests (Figs 2 and 3). This is in contrast to the work by van Mantgem et al. (2009) that ruled out a strong role of atmospheric pollutants on western forests. The strongest effect appears to be due to the effects of long-term acidification, particularly in the northeast."

INTERACTIONS WITH OTHER FACTORS

NATIONAL

Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J., and Emberson, L. D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. Annual Review of Plant Biology, 63, 637-661. doi:10.1146/annurev-arplant-042110-103829

"Interactions [between climate and O3 affecting the incidence and distribution of pests and diseases] may also occur with increased nitrogen deposition to nitrogen-limited ecosystems because insect herbivores are frequently limited by nitrogen availability."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Air pollution can negatively affect the health and productivity of NFs [National Forests], and the fragmented landscape in which many NFs are situated impedes important ecosystem processes, including migration."

Mickley, L. J., Jacob, D. J., Field, B. D, & Rind, D. (2004). Effects of future climate change on regional air pollution episodes in the United States. Geophysical Research Letters, 31 (L24103), 1-4.

"Results show that the severity and duration of summertime regional pollution episodes in the midwestern and northeastern United States increase significantly relative to present. Pollutant concentrations during these episodes increase by 5–10% and the mean episode duration increases from 2 to 3–4 days. These increases appear to be driven by a decline in the frequency of mid-latitude cyclones tracking across southern Canada."

R9: EASTERN

Swank, W. T., & Vose, J. M. (1991). Watershed-scale responses to ozone events in a pinus strobus l. plantation. Water, Air, and Soil Pollution, 119-133.

"Ozone stress did not predispose trees to root pathogens or bark beetle attack."

MERCURY

NATIONAL

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43, 52-63. doi:10.1016/j.atmosenv.2008.09.051

"Increased volatilization of mercury from ocean and land reservoirs as a result of climate change would transfer mercury between ecosystems via atmospheric transport, re-depositing it in a more mobile and presumably more toxic form. Volatilization of mercury from the ocean is directly affected by warming (lower solubility of elemental mercury) and would also be affected by changes in ocean biology and circulation (Strode et al., 2007; Sunderland and Mason, 2007)."

"Soil mercury is mainly bound to organic matter (Ravichandran, 2004). Future warming at boreal latitudes could release large amounts of soil organic matter to the atmosphere as CO2, both through increased respiration (Raich and Schlesinger, 1992) and increased fires (Spracklen et al., submitted for publication)."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Mercury deposition negatively affects aquatic food webs as well as terrestrial wildlife, as a result of bioaccumulation, throughout the United States (Chen et al., 2005; Driscoll et al., 2007; Peterson et al., 2007)."

OZONE

NATIONAL

Aber, J. D., Neilson, R. P., McNulty, S., Lenihan, J. M., Bachelet, D. & Drapek, R. J. (2001). Forest processes and global environmental change: Predicting the effects of individual and multiple stressors. BioScience, 51(9), 735-751.

"Unlike N deposition, the effects of ozone on ecosystems are direct and immediate, because the primary mechanism for damage is through direct uptake from the atmosphere into plant leaves through the stomates. Ozone is a strong oxidant that damages cell membranes and requires the plant to increase its energy expenditures to repair these sensitive tissues. The net effect is a decline in net photosynthetic rate. "

Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J., and Emberson, L. D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. Annual Review of Plant Biology, 63, 637-661. doi:10.1146/annurev-arplant-042110-103829

"In addition to fixing less CO2, plants growing in elevated O3, [tropospheric ozone] commonly have higher rates of mitochondrial respiration. This has been observed in numerous crops, including soybean (Gillespie et al. 2012), wheat (Biswas et al. 2008), rice (Imai & Kobori 2008), and bean (Phaseolus vulgaris) (Amthor 1988), as well as several tree species, including Scots pine (Pinus sylvestris) (Kellomäki & Wang 1998), beech (Fagus sylvatica) (Kitao et al. 2009), and aspen (Populus tremuloides) (Karnosky et al. 2005, Volin & Reich 1996)."

"Reductions in O3 uptake would also lead to increased atmospheric [O3] in the boundary layer; in fact, a doubling of [CO2] was estimated to increase [O3] over parts of Europe, Asia, and the Americas by 4–8 ppb during the crop growing season (Sanderson et al. 2007). However, the relationship between stomatal conductance and [CO2] may prove to be more complex than is often assumed, and elevated [CO2] may not completely alleviate the adverse effect of O3 (Uddling et al. 2010)."

"There is evidence from long-term field experiments that O3 can significantly alter carbon cycling and reduce the increase in forest soil carbon sequestration caused by elevated [CO2] (Karnosky et al. 2005, Loya et al. 2003)."

"Atmospheric [CO2] and [O3] also have the potential to alter nitrogen cycling in forest ecosystems through influences on plant growth and litter production. Generally, CO2 stimulates photosynthesis, leaf, and root litter production, whereas O3 damages photosynthetic tissues and accelerates leaf senescence. The interactions between O3, CO2, and nitrogen are complex and dependent on plant and soil microbial processes, which feed back on nitrogen availability (Holmes et al. 2006)."

"As atmospheric [CO2] increases in the future, the global climate will change. In particular, temperature will increase and precipitation will change, and both are important determinants of stomatal conductance, NPP [net primary productivity], and O3 [ozone] uptake. As such, reduced stomatal conductance that occurs in response to elevated [CO2] may enhance plant water-use efficiency, which could help to partly alleviate the effects of reduced rainfall (Leakey et al. 2009). Increased water stress in a warmer climate may also decrease sensitivity to O3 through reduced uptake (Fuhrer 2009); however, O3-induced damage to stomatal functioning (Maier-Maercker 1999, Mills et al. 2009, Wilkinson & Davies 2009, Wilkinson & Davies 2010) might confound this effect."

"Higher temperatures and altered precipitation can also affect O3 [atmospheric ozone] formation through alterations to natural emissions of O3 precursors."

"It is clear that changes in temperature and precipitation that accompany rising atmospheric [CO2] have the potential to alter O3 [ozone] production and deposition rates as well as plant responses to O3."

"There is also limited evidence to suggest that O3 [ozone] can affect CH4 [methane] emissions from peatlands, possibly through O3 causing plants to alter substrate availability to soil microbes or causing changes in transport of CH4 through vascular plants with aerenchymatous tissue (Toet et al. 2011)."

"Finally, as the climate changes, so can the incidence and distribution of pests and diseases; because studies have also shown that O3 can mediate such impacts, either by causing toxicity to the secondary stress or by affecting the abundance and quality of the host plant (Flückiger et al. 2002, Fuhrer 2009, Fuhrer & Booker 2003), interactions between climate and O3 on the prevalence of such secondary stresses should also be considered."

Avise, J., Chen, J., Lamb, B., Wiedinmyer, C., Guenther, A., Salathe, E. & Mass, C. (2009). Attribution of projected changes in summertime US ozone and PM2.5 concentrations to global changes. Atmospheric Chemistry and Physics, 9, 1111 – 1124.

"Projected meteorological changes (futMETcurLU simulation) result in an overall decrease (−1.3 ppbv) in US average DM8H [average daily maximum 8-h] ozone. Meteorological impacts are spatially highly variable. The largest increases in average DM8H ozone (approximately +4 ppbv), are found in the northeast and west central regions. Our results for the northeast are in agreement with Hogrefe et al. (2004b) who found that climate change resulted in an increase of roughly 4 ppbv in average DM8H ozone, as well as, Racherla and Adams (2008) who found that climate change based on the A2 scenario increased 95th percentile ozone in the Eastern US by approximately 5 ppbv."

"In the west central region, increased temperature and reduced cloud cover may be somewhat offset by increases in daytime PBL [planetary boundary layer] height, but the overall result is an increase in average DM8H [average daily maximum 8-h] ozone. In the northeast, increased average DM8H ozone appears to be due to a combination of increased temperature with only small increases in daytime PBL heights, as well as decreased cloud cover. The largest decreases in average DM8H ozone appear in the south and southwestern regions (−6 ppbv), with smaller decreases occurring along the west coast and northern regions (approximately −1 ppbv). The smaller decrease along the west coast is in contrast with Steiner et al. (2006) who found that climate change alone would increase ozone 3-10% throughout California. "

"Overall, US July average DM8H [average daily maximum 8-h] ozone concentrations in the 2050's are projected to increase by an average of +7 ppbv compared to the present-day. However, these results are spatially highly variable. Some regions may experience larger increases in average DM8H ozone, while other regions may experience decreases in average DM8H ozone."

Bedsworth, L. (2011). Air quality planning in California's changing climate. Climatic Change, DOI 10.1007/s10584-011-0244-0, 1-18.

"If emissions continue to increase in developing countries as predicted, the contribution of background ozone concentrations to local air pollution levels in the United States will likely increase (Fiore et al. 2002a). Increases in global background ozone concentrations could prolong the ozone season in the United States (Fiore et al. 2002b). On balance, the increase in global background ozone levels will reduce the effectiveness of local emission reduction measures and make it more difficult to attain air quality standards (Fiore et al. 2002a; Fiore et al. 2002b; Lin et al. 2000)."

Bytnerowicz, A., Omasa, K., & Paoletti, E. (2007). Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. Environmental Pollution, 147, 438-445.

"Climate change, especially high radiation and temperature, promote increases in tropospheric ozone (O3), the secondary pollutant generated from the GHGs [greenhouse gases] non-methane volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx). O3 is a potent GHG itself and indirectly influences lifetimes of other GHGs such as CH4 (Fiore et al., 2002)."

Carpenter, S. R., Fisher, S. G., Grimm, N. B., & Kitchell, J. F. (1992). Global change and freshwater ecosytems. Annual Review Ecological Systems, 119-139.

"The effects of ozone in increasing tree water use were also detectable in the surface soils in proximity to the trees for which sap flow was measured. Estimated soil moisture (% volume) ranged from 7 to 22% at Look Rock in 2002. Analyses revealed increasing importance of O3 exposure on soil water status in 2002, just as was found with canopy conductance. In 2001, preceding rainfall and VPD [Vapor Pressure Deficit] were the most significant influences on soil moisture status, whereas VPD, water withdrawal (sap flow) and O3 became increasingly important in 2002."

Chen, J., Avise, J., Lamb, B., Salathe, E., Mass, C., Guenther, A., … & Larkin, N. (2009). The effects of global changes upon regional ozone pollution in the United States. Atmospheric Chemistry and Physics, 9, 1125 – 1141.

"The collective effects of global and regional changes were projected to cause poorer air quality in the US. The magnitudes of pollution changes varied spatially and temporally Fig. 8 shows the spatially averaged DM8H ozone [daily maximum 8-h moving average] comparisons by month and over the entire year.

The annual DM8H ozone in the US was projected to increase by +9.6 ppbv (22%) from the base case of 44 ppbv. The inter-annual ozone variability was similar for the current and the future cases: the 10-year DM8H ozone standard deviations for the base case and the future case were 10 ppbv and 11 ppbv, respectively. The annual DM8H ozone standard deviations were larger than the monthly values of 3–5 ppbv because ozone mixing ratios are higher during summers but lower during the rest of the months."

"Future monthly averaged DM8H [daily maximum 8-h moving average] ozone mixing ratios were projected to be higher in all months by between +8 and +13 ppbv. The rate of increase was larger in the winter and spring than the rest of the year. In the winter and spring, the projected DM8H ozone increased by 28%, while in the summer months it increased by 17%. The differences are attributed to higher future chemical boundary conditions as well as decreases in PBL height [boundary layer height] during the winter."

"The projected poorer ozone air quality in the future was also reflected in the average number of days when ozone exceeds the new US EPA ambient air quality standard of 75 ppbv (Fig. 9). Episodic ozone events were projected to occur more frequently in all months except the winter. The largest increase in episodic ozone frequency occurred in the spring. Annually, episodic ozone days were projected to increase more than 3 times from the base case of 10 days per year. In the summer, the average ozone episode frequency was projected to increase to approximately 6.7 days from the base case of 2.6 days per year. Since ozone attainment is determined by the 4th highest annual DM8H ozone [daily maximum 8-h moving average] averaged over 3 years, increasing the frequency of ozone exceeding 75 ppbv on an annual basis will increase the likelihood of regions violating the ozone standard."

"Under the combined impacts of global change, the ozone pollution season was projected to be longer, with diminished seasonal difference between the spring and summer months (Fig. 9). In the 2050s, the average US ozone season was projected to start as early as March and end in October. In both the base case and the future case, ozone events occur most frequently in July when surface temperature was also the highest."

"Spatial comparisons also showed future ozone pollution to impact more areas within the US. Quantitatively, of the 6094 domain grids representing the contiguous US, 86% were projected to have DM8H ozone [daily maximum 8-h moving average] exceeding the 75 ppbv standard at least once per year, and 76% were to exceed the standard by at least four times per year. This represents a 38% increase in areas experiencing high ozone levels compared to the base case, and the possibility of 79% increase in areas that were designated as non-attainment with the federal ozone standard. Larger fractions of rural regions were projected to have high ozone conditions in 2050s. Most of these occurrences were in spring and summer months when conditions are favorable to ozone chemistry."

"Across the regions, the average DM8H ozone [daily maximum 8-h moving average] were estimated to increase by 9–15 ppbv in the spring and 6–13 ppbv in the summer. The south central US (R06) had the largest ozone increase compare to the base case, with 15 ppbv (+29%) and 13 ppbv (+22%) increases, respectively for spring and summer months. In contrast, the Northwestern US (R10) had the least amount of change with 9 ppbv (+24%) and 6 ppbv (+16%) increases. In the fall season, the regional changes were more homogeneous between 6 ppbv and 9 ppbv. The Southwestern US (R08) had the largest estimated increase of +25% from the base case of 37 ppbv, and the southern Midwest region (R07) had the least amount of change, with 6 ppbv (+16%) increase from the base case of 38 ppbv."

Felzer, B. Felzer, B., Kicklighter, D., Melillo, J., Wang, C., Zhuang, Q., & Prinn, R. (2007). Impacts of ozone on trees and crops. C.R. Geoscience, 784-798.

"Visible injury resulting from chronic exposure to low ozone concentrations includes changes in pigmentation or bronzing, chlorosis, and premature senescence after chronic exposure to low ozone concentrations. Flecking and stippling may occur after acute exposure to high ozone levels. For some tree species, such as yellow poplar [Liriodendron tulipifera], loblolly pine [Pinus taeda], and white pine [Pinus strobus], there is a correlation between visible injury and reductions in growth, while in many studies for a wide range of species, including some of the above, there does not appear to be a correlation "

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43, 52-63. doi:10.1016/j.atmosenv.2008.09.051

"Coupled GCM–CTM studies find that climate change alone will increase summertime surface ozone in polluted regions by 1–10 ppb over the coming decades, with the largest effects in urban areas and during pollution episodes."

"Higher water vapor in the future climate is expected to decrease the ozone background, so that pollution and background ozone have opposite sensitivities to climate change."

"The most important climate variables affecting tropospheric ozone on a global scale are stratosphere-troposphere exchange, lightning NOx, and water vapor. These three variables are all expected to increase in the future climate; the first two cause an increase in ozone and the third a decrease. Different models thus project changes in the global tropospheric ozone burden over the 21st century ranging from -5% to +12% (Wu et al., 2008b)."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"A combination of hot, stagnant summer air masses, expansive forest area, and high rates of NOx emissions combine to produce high levels of ozone, especially in the western, southern, and northeastern regions of the United States (Fiore et al., 2002)."

"Exposure to ozone may further exacerbate the effects of drought on both forest growth and stream health (McLaughlin et al., 2007a; 2007b)."

Leung, L. R. & Gustafson, W. I. (2005). Potential regional climate change and implications to U.S. air quality. Geophysical Research Letters, 32 (L16711), 1-4. doi:10.1029/2005GL022911

"During summer, Texas is marked by warming (1–3°C), increased downward solar radiation (up to 40 W/m2), less frequent rainfall (more than 8 days less per season), and slightly more frequent stagnation (up to 4 days more per season) that all suggest an increase in ozone concentrations. One exception, however, is the extension of ventilation time by about 2 hours during the early morning hours. The opposite conditions are found in the Midwest with very small warming or even cooling, reduced downward solar radiation (up to 30 W/m2), more frequent rainfall (up to 6 days more per season), less frequent stagnation (up to 8 days less per season), and reduced ventilation (up to 3 more unvented hours per day). Depending on the relative impacts of these parameters, ozone concentrations may remain similar or slightly decrease, based on the simulated atmospheric changes alone."

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Crosby, B. J., Dunscomb, J. K., . . . Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the Eastern United States. Annals of the New York Academy of Sciences, 1162, 99-135.

"Ozone is a well-studied pollutant known to be toxic to plants and animals. In plants, O3 appears to affect membrane function, leading to reduction in photosynthesis, slower growth, and in severe cases, death."

"Because species vary in their sensitivity, O3 can shift the competitive balance in plant communities to the detriment of sensitive species (Miller and McBride 1999). Further, because individuals of a given species vary in their sensitivity, O3 exposure can cause changes in genetic structure of populations, reducing or eliminating sensitive genotypes (Taylor et al. 1991; Davison & Reiling 1995)."

McLaughlin, S. B., Nosal, M., Wullschleger, S. D., & Sun, G. (2007). Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist, 174(1), 109-124. doi:10.1111/j.1469-8137.2007.02018.x

"While increasing temperatures and reduced rainfall will reduce water availability for tree use, they are not the only components of climate change that will probably affect forest water balance. There is abundant evidence that tropospheric ozone (O3), which, like emissions of greenhouse gases, is a byproduct of fossil fuel combustion, can alter trees' capacity to control water loss through stomata and hence their potential sensitivity to drought (Maier-Maercker, 1998; Mansfield, 1998)."

Mickley, L. J. (2007). A future short of breath? Possible effects of climate change on smog. Environment, 49 (6), 35-43.

"One recent study examined the relationships of surface ozone concentrations and temperature in the summer across several regions—California, the southeastern United States, and the Northeast—for the 1980–1998 period (Lin 2001). The researchers found that the probability of exceeding the EPA ozone standard of 84 parts per billion (ppb) increased significantly with increasing temperature, particularly in the Northeast. There the probability jumped dramatically, from 5 percent at 84°F to 18 percent at 91°F, 42 percent at 98°F, and 66 percent at 104°F. In the 1980–1998 period, surface temperatures above 100°F rarely occurred. However, in the future, such temperatures may become more common."

Mohan, J. E., Cox, R. M., and Iverson, L. R. (2009). Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. Canadian Journal of Forest Research, 39, 213-230. doi:10.1139/X08-185

"The effect of O3 will offset expected gains in forest water-use efficiency with increased CO2 and is likely to increase water stress (Hsiao et al. 1976) in a warmer climate with more droughts (Hanson and Weltzin 2000)."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"While ozone concentrations are projected to increase for many regions, climate change, on a global scale, is expected to generally accelerate tropospheric ozone destruction due to catalyzed photodegradation in the presence of increased atmospheric water vapor. For example, Racherla and Adams (2006) project a 5% decline in global tropospheric ozone concentrations in the 2050s from 1990s levels using present day pollutant emission scenarios. Dentener et al. (2006) and Stevenson et al. (2006) estimated future ozone concentrations for 2030 based on current levels of emissions. They calculated that climate change could reduce global ozone by 0.5–1.0 ppb over the continents and 1–2 ppb over the oceans."

Ryan, M., Archer, S., Birdsey, R., Dahm, C., Heath, L., Hicke, J. ., . . . Schlesinger, W. (2008). Land resources. in: The effects of climate change on agriculture, land resources, water resources, and biodiversity. a report by the U.S. climate change

science program and the subcommittee on global change research. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 362.

"In the United States, controls on emissions of nitrogen oxides and volatile organic compounds are expected to reduce the peak ozone concentrations that currently cause the most plant damage (Ashmore 2005). However, background tropospheric concentrations may be increasing as a result of increased global emissions of nitrogen oxides (Ashmore 2005). These predicted increases in background ozone concentrations may reduce or negate the effects of policies to reduce ozone concentrations (Ashmore 2005)."

"Ozone pollution will modify the effects of elevated CO2 and any changes in temperature and precipitation (Hanson et al. 2005), but these interactions are difficult to predict because they have been poorly studied."

Wu, S., Mickley, L. J., Leibensperger, E. M., Jacob, D. J., Rind, D. & Streets, D.G. (2008). Effects of 2000 – 2050 global change on air quality in the United States. Journal of Geophysical Research, 113 (D06032), 1 – 12. doi:10.1029/2007JD008917

"The A1B scenario for 2000–2050 projects large decreases in U.S. anthropogenic emissions of ozone precursors (40% for NOx) to improve air quality. We find that these decreases under 2000 climate conditions reduce the mean summer daily maximum 8-hour average ozone by 2–5 ppb in the western United States and 5–15 ppb in the east. On the other hand, we find that climate change increases the mean summer daily maximum 8-hour average ozone by 2–5 ppb over large areas in the United States, with maximum effect over the Midwest. Little effect from climate change is found in the southeast."

R8: SOUTHERN

Mclaughlin, S., & Percy, K. (1999). Forest health in north america: Some perspectives on actual and potential roles of climate and air pollution. Water, Air, and Soil Pollution, 151-197

"A summary of the results of controlled exposure studies with seedlings and saplings of southern pines in open-topped chambers in the SCFRC (Southern Commercial Forest Research Cooperative) indicated that significant growth reductions occurred with increased ozone exposure."

McLaughlin, S. B., Nosal, M., Wullschleger, S. D., & Sun, G. (2007). Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist, 174(1), 109-124. doi:10.1111/j.1469-8137.2007.02018.x

"These studies [from southern Appalachian forests] indicate that ozone is an important component of the current climate, and that anthropogenic contributions of ozone will probably exacerbate the adverse effects of global warming by reducing the water available to support both forest and stream ecosystems. Changes in patterns of water use and retention by terrestrial systems can be expected to amplify the effects of drought, particularly late in the growing season when water use by vegetation most strongly influences baseflow of streams."

R9: EASTERN

Gauthier, M. –M. & Jacobs, D. F. (2011). Walnut (Juglans spp.) ecophysiology in response to environmental stresses and potential acclimation to climate change. Annals of Forest Science, 68(8), 1277-1290. doi: 10.1007/s13595-011-0135-6

"Results from King et al. (2005) also indicate that 34–45% increases in elevated O3 significantly reduced NPP of [northern] hardwood forests by 13–24% compared to nontreated controls. Thus, exceedances of O3 air quality standards could mitigate or offset biomass gains from elevated CO2 (Mohan et al. 2009) and exacerbate effects of increased temperatures and drought on forest growth in temperate hardwoods (McLaughlin et al. 2007a, b)."

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43, 52-63. doi:10.1016/j.atmosenv.2008.09.051

"Significant ozone increases in the northeastern U.S. are found in all the models of Table 2. This likely reflects the strong sensitivity of ozone in that region to temperature and to the frequency of frontal passages, for which climate projections are consistent across GCMs."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"Current levels of ozone exposure are estimated to reduce eastern and southern forest productivity by 5-10% (Joyce et al., 2001; Felzer et al., 2004)."

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E., Crosby, B. J., Dunscomb, J. K., . . . Weathers, K. C. (2009). Effects of air pollution on ecosystems and biological diversity in the Eastern United States. Annals of the New York Academy of Sciences, 1162, 99-135.

"Ozone exposure studies in Finland show the important sedge Eriophorum vaginatum to be relatively insensitive to ozone; however, several of the tree species that are commonly found in or around wetlands in the eastern United States are considered sensitive to O3 [e.g., green ash (Fraxinus pennsylvanica), speckled alder (Alnus rugosa)] (National Park Service 2003). Even within the important Sphagnum genus of bryophytes, some species are sensitive to O3 and some are not (Gagnon and Karnosky 1992; Potter et al. 1996.)"

Mickley, L. J. (2007). A future short of breath? Possible effects of climate change on smog. Environment, 49 (6), 35-43.

"Most studies have estimated significant increases in peak summertime ozone concentrations in the midwestern and northeastern United States (see Figure 2 on page 42). For example, some studies estimate that climate change in this region could increase daily average peak ozone concentrations by as much as 5 ppb by 2050, enough to tip the air quality index from "moderate" to "unhealthy" levels (Hogrefe et al 2004, Murazaki 2006). Another study found that during pollution episodes in the Midwest and Northeast, ozone concentrations could jump by as much as 10 ppb in the future climate (Wu 2006). Still another study showed that the impact of climate change on ozone concentrations over this region could be mitigated significantly if trends in energy use followed a less fossil-fuel intensive scenario (Tao

NORTH ATLANTIC

Kunkel, K. E., Huang, F.-C., Liang, H.-Z., Lin, J.-T., Wuebbles, D., Tao, Z., Williams, A. , … & Hayhoe, K. (2008). Sensitivity of future ozone concentrations in the northeast USA to regional climate change. Mitigation and Adaptation Strategies for Global Change, 13, 597-606. doi: 10.1007/s11027-007-9137-y

"Such changes [in temperature as predicted by climate models] could affect ozone concentrations and the number of days exceeding the national standard due to the sensitive dependence on temperature (e.g., Wuebbles et al. 1989; Sillman and Samson 1995)."

"Both mean daily and 8-h [hour] maximum ozone increase (by about 10–25% for the higher emissions scenario and 0–10% for the lower emissions scenario) from the combination of three factors, all tending to favor higher concentrations: (1) higher temperatures lead to changes in the rates of reactions and photolysis rates important to the ozone chemistry (e.g., more thermal decomposition of peroxyacetyl nitrate (PAN), which leads to more nitrogen oxides (NOx) and odd hydrogen (e.g., OH, HO2, etc) and thus more ozone production in the daytime. Overall the ozone production increases with increased temperature (e.g., Sillman and Samson 1995; Tao et al. 2007); (2) lower cloudiness (higher solar radiation) increases the photolysis reaction rates; and (3) higher biogenic emissions increase the concentration of reactive species used in ozone production."

Mohan, J. E., Cox, R. M., and Iverson, L. R. (2009). Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. Canadian Journal of Forest Research, 39, 213-230. doi:10.1139/X08-185

"Needle blights of eastern white pine (Pinus strobus) have been reported since the turn of the twentieth century (Clinton 1907; Faull 1920). Later this injury was linked to O3 exposure by Linzon (1967) and Berry and Ripperton (1963)."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"Models of the New York metropolitan area have been used to estimate average summertime ozone increases from 0.3 ppb in the 1990s to 4.3 ppb by the 2050s (Knowlton et al., 2004)."

SOUTH ATLANTIC

Chappelka, A. H., & Samuelson, L. J. (1998). Ambient oxone effects on forest trees of the eastern united states: A review. New Phytol, 139, 91-108.

"After the occurrence of several unusually high ozone episodes (0±08±0±120 ll l−") during the 1984 growing season, Swank & Vose (1991) observed chlorotic mottling and tip-burn on eastern white pine [Pinus strobus] in a 13±4-ha watershed located in the southern Appalachian Mountains near the Georgia and North Carolina border. They observed premature senescence of foliage and reduced basal area increment, and related this to the observed ozone episodes. This growth depression was short term and tree growth recovered after a couple of years. "

McLaughlin, S. B., Nosal, M., Wullschleger, S. D., & Sun, G. (2007). Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist, 174(1), 109-124. doi:10.1111/j.1469-8137.2007.02018.x

"This 12,500 ha forested watershed [Cataloochee Creek, North Carolina] draining north-east slopes of the Great Smoky Mountains National Park had continuous streamflow data for 22 yr (1982–2003), but O3 data were available for only 15 yr. The exploratory regression model for average streamflow (August–October) was highly significant ($P < 0.01$, $n = 15$) with R2 = 0.75, and included terms for both cumulative ozone exposure (sumO60) and PDSI [Palmer Drought Severity Index]. Ozone exposure was significant at $P < 0.01$."

Soulй, P. T. (2011). Changing Climate, Atmospheric Composition, and Radial Tree Growth in a Spruce-Fir Ecosystem on Grandfather Mountain, North Carolina. Natural Areas Journal, 31(1) 65-74. doi: 10.3375/043.031.0108

"Other aspects of changing atmospheric conditions, including ozone (O3), carbon dioxide (CO2), and increasing temperature may impact high elevation spruce-fir ecosystems. For red spruce [Picea rubens], Rebbeck et al. (1993) reported large (up to 40%) drops in net photosynthesis for trees exposed to high O3 concentrations."

Zhang , C., Tian, H., Chappelka, A. H., Ren, W., Chen, H., Pan, S., Liu, M., Styers, D. M., Chen, G., and Wang, Y. (2007). Impacts of climatic and atmospheric changes on carbon dynamics in the Great Smoky Mountains National Park. Environmental Pollution, 149(3):336-347. oi:10.1016/j.envpol.2007.05.028

"Our ozone data set [from Great Smokey Mountains National Park] shows that the annual average AOT40 [accumulated dose of ozone over a threshold of 40 ppb during daylight hours] increased from 1418 ppb-h in 1971 to 3194 ppb-h per 30 days in 2001."

SOUTH CENTRAL

Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J., and Emberson, L. D. (2012). The effects of tropospheric ozone on net primary productivity and implications for climate change. Annual Review of Plant Biology, 63, 637-661. doi:10.1146/annurev-arplant-042110-103829

"One of the few examples of observational data investigating responses to [O3, stomatal conductance, and CO2] stress combinations is that collected for a mixed deciduous forest in eastern Tennessee, United States (McLaughlin et al. 2007a). These data suggest an increase in water use under warmer climates with high [O3], with subsequent growth limitations for mature forest trees and implications for the hydrology of forest watersheds (McLaughlin et al. 2007b)."

Hanson, P.J., Wullschleger, S., Norby, R. J., Tschaplinski, T. J., Gunderson, C. A. (2005). Importance of changing co2, temperature, precipitation, and ozone on carbon and water cycles of an upland-oak forest: Incorporating experimental results into model simulations. Global Change Biology, 1402-1423.

"The majority of the tree species found on Walker Branch Watershed do not show significant growth responses to incremental increases in O3 exposure."

McLaughlin, S. B., Nosal, M., Wullschleger, S. D., & Sun, G. (2007). Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist, 174(1), 109-124. doi:10.1111/j.1469-8137.2007.02018.x

"The effects of ozone in increasing tree water use were also detectable in the surface soils in proximity to the trees for which sap flow was measured. Estimated soil moisture (% volume) ranged from 7 to 22% at Look Rock [Tennessee] in 2002. Analyses revealed increasing importance of O3 exposure on soil water status in 2002, just as was found with canopy conductance."

"Enhancement of the amplitude of the daily water-loss and recovery cycles observed in the present study [at Look Rock, Tennessee] following highest ozone exposures suggest an ozone-induced interference in whole-tree water balance. Such patterns would probably result from ozone-induced increases in daytime transpiration."

"Despite rather low levels of expected regional drought indicated for this region [southern Appalachian forests] by the PDSI [Palmer Drought Severity Index], the soils at Look Rock [Tennessee] became very dry within a period of approx. 2 wk during high ozone exposures in late summer (Fig. 3). Canopy conductance and soil-moisture analyses suggested that ozone contributed to the rapid loss of water from the rooting zone of trees, and had exacerbated water stress at this site."

"Our data [at Look Rock Tennessee] suggest that ozone uptake by vegetation in our region [southern Appalachian forests] will probably be increased both directly by higher ozone exposure, and indirectly in response to increased canopy conductance during higher-ozone episodes."

EAST

Dietze, M. C., & Moorcroft, P. R. (2011). Tree mortality in the eastern and central United States: patterns and drivers. Global Change Biology, 17, 3312-3326. doi: 10.1111/j.1365-2486.2011.02477.x

"The impacts of ozone were consistently negative as hypothesized and as expected angiosperms were more sensitive to ozone than conifers (average sensitivity of 2.3 vs. 0.8). The differences in mortality rates among functional types conforms roughly to the differences in the impact of ozone on growth rates found in a recent meta-analysis (Wittig et al., 2007), which themselves follow the different patterns of stomatal conductance among species."

Hogrefe, C., Lynn, B., Civerolo, K., Ku, J. Y., Rosenthal, J., Rosenzweig, C., ... & Kinney, P. L. (2004). Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. Journal of Geophysical Research, 109(D22), D22301. doi:10.1029/2004JD004690

"For the 2020s, increases in summertime average daily maximum 8-hour O3 concentrations range from 0 to 8 ppb. The largest increases of 4–8 ppb are predicted for the urban corridor from Washington, D. C., to Massachusetts, while O3 changes are small for the southern and western portion of the modeling domain. Predicted changes in average summertime daily maximum 8-hour O3 concentrations for the 2050s are similar in magnitude but occur over a larger area compared to those in the 2020s. In contrast to the 2020s the largest O3 increase of 4–8 ppb is predicted for the Midwest and the southeastern United States. For the 2080s, predicted O3 increases exceed 7 ppb for the entire urban corridor from Washington, D. C., to New York City and for the Ohio River Valley. However, summertime average 8-hour daily maximum O3 concentrations are predicted to decrease for the southern and northern thirds of the modeling domain [eastern US]."

"When the increases of summertime average daily maximum 8-hour O3 concentrations are spatially averaged over the locations of the population oriented O3 monitors [in the eastern US] depicted in Figure 1, the increases are 2.7, 4.2, and 5.0 ppb for the 2020s, 2050s, and 2080s, respectively."

"To analyze changes in the frequency and duration of extreme O3 events [in the eastern US], the number of days for which the predicted daily maximum 8-hour O3 concentrations exceeded 84 ppb was determined at the locations of the O3 monitors shown in Figure 1, and for each such event the number of consecutive days for which these conditions persisted was tracked. The results of this analysis are presented in Figures 3a–3b. Figure 3a shows the total number of days with daily maximum 8-hour O3 concentrations exceeding 84 ppb for the 1990s, 2020s, 2050s, and 2080s simulations, grouped by the number of consecutive days on which this concentration was exceeded. The total number of exceedance days increased from ~20,000 in the 1990s to ~26,000 in the 2020s, ~33,000 in the 2050s, and ~35,000 in the 2080s, i.e., by roughly 75% by the 2080s."

"To highlight changes in the persistence of extreme O3 events [in the eastern US], Figure 3b presents normalized frequencies of occurrence of pollution episodes of different length. Figure 3b illustrates that for the 1990s, 60% of all high- O3 events lasted only for a single day, while for the 2080s, more than 50% of all O3 events lasted for at least 2 days."

"In summary, the CMAQ [Community Multiscale Air Quality] simulations of O3 concentrations utilizing the 2020s, 2050s, and 2080s A2 regional climate fields from the GISS-MM5 [Goddard Institute for Space Studies (GISS) 4° x 5° resolution Global Atmosphere-Ocean Model (GISS-GCM) coupled with the National Center for Atmospheric Research mesoscale regional climate model (MM5)] simulations (Lynn et al., submitted manuscript, 2004) show an increase in summertime average daily maximum 8-hour O3 concentrations, interannual variability of median O3 values, and an increase in the frequency and duration of extreme O3 events over the eastern United States in the absence of changes in anthropogenic emissions and boundary conditions."

Mohan, J. E., Cox, R. M., and Iverson, L. R. (2009). Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. Canadian Journal of Forest Research, 39, 213-230. doi:10.1139/X08-185

"Abundant empirical evidence indicates that O3 exposure reduces stomatal control of transpiration and in larger trees leads to greater stomatal apertures, increased transpiration, and delayed stomatal closure at nightfall, leading to decreased water-use efficiency (McLaughlin et al. 2007). Slowdowns in seasonal tree growth patterns in the southern Appalachians by 30%–50% were attributed, in part, to O3- induced poor water-use efficiency (McLaughlin et al. 2007)."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"Similarly, using the IPCC A2 high CO2 emission scenario, Hogrefe et al. (2004) estimate increases in summertime average daily maximum 8-hour ozone concentrations over the eastern U.S. of 2.7 ppb by the 2020s, 4.2 ppb by the 2050s, and 5.0 ppb by the 2080s."

SMOKE AND FINE PARTICULATES

NATIONAL

Avise, J., Chen, J., Lamb, B., Wiedinmyer, C., Guenther, A., Salathe, E. & Mass, C. (2009). Attribution of projected changes in summertime US ozone and PM2.5 concentrations to global changes. Atmospheric Chemistry and Physics, 9, 1111 – 1124.

"Climate change tends to reduce PM2.5 concentrations in most regions, with the largest reductions coming in the Southeastern US due to enhanced wet deposition from an increase in convective precipitation."

Bedsworth, L. (2011). Air quality planning in California’s changing climate. Climatic Change, DOI 10.1007/s10584-011-0244-0, 1-18.

"The relationship between PM [particulate matter] and warming, on the other hand, is more complex. Some particulate matter, specifically black carbon (soot) from combustion (largely from diesel engines) contributes to global warming (Jacobson 2002). Therefore, reducing black carbon levels could have a positive climate effect. On the other hand, other components of particulate matter, such as sulfates, have a net cooling effect. These aerosols reflect incoming solar and infrared radiation and affect cloud formation (Forster et al. 2007). Modeling has shown that an abrupt reduction in aerosol concentrations could enhance warming (Brasseur and Roeckner 2005). Therefore, particulate matter poses an interesting challenge—from a public health standpoint, its reduction is necessary, but in some cases this reduction could aggravate global warming."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"Decreased concentrations of atmospheric fine PM [particulate matter] are projected in regions that experience increases in precipitation due to enhanced scavenging of PM by water molecules. Racherla and Adams (2006) estimate that increases in precipitation and wet deposition loss rates could decrease the global burdens and atmospheric residence times of PM2.5 by 2–18% by the 2050s (Fig.1, Legend Item E). However, changes in other climate variables may also affect PM concentrations."

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2012). Impact of 2000–2050 climate change on fine particulate matter (PM2. 5) air quality inferred from a multi-model analysis of meteorological modes. Atmospheric Chemistry and Physics Discussions, 12, 18107-18131. doi:10.5194/acpd-12-18107-2012

"Tai et al. (2012) pointed out that increasing mean temperature, independently from changes in circulation, could have a large effect on PM2.5 [fine particulate matter] in the Southeast and some parts of the Western US through biogenic emissions, wildfires, and nitrate aerosol volatility."

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2010). Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. Atmospheric Environment, 44(32), 3976-3984. doi:10.1016/j.atmosenv.2010.06.060

"We find a strong positive correlation of observed PM2.5 [fine particulate matter] with temperature driven mainly by sulfate and OC [organic carbon], in contrast to previous CTM [chemical transport model] sensitivity studies that perturbed temperature only and found a negative response (Aw and Kleeman, 2003; Dawson et al., 2007; Kleeman, 2008)."

"Changes in precipitation patterns can obviously affect PM2.5 [fine particulate matter] concentrations, as reflected in the negative observed correlation."

R8: SOUTHERN

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2012). Impact of 2000–2050 climate change on fine particulate matter (PM2. 5) air quality inferred from a multi-model analysis of meteorological modes. Atmospheric Chemistry and Physics Discussions, 12, 18107-18131. doi:10.5194/acpd-12-18107-2012

"Temperature-driven changes in the southeast may reduce ammonium nitrate by ~0.2 μgm^{-3} due to increased volatility (Pye et al., 2009; Tai et al., 2012), but increase organic PM [particulate matter] by ~0.4 μgm^{-3} due to increased biogenic emissions (Heald et al., 2008; Tai et al., 2012)."

EAST

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43, 52-63. doi:10.1016/j.atmosenv.2008.09.051

"Racherla and Adams (2006) find a global decrease in PM2.5, as would be expected from the global precipitation increase, but a regional increase in the eastern U.S. due to lower precipitation there. Differences between GCM/RCMs in the regional precipitation response to climate change are a major cause of discrepancy in the PM response (Racherla and Adams, 2006; Pye et al., in press)."

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2012). Impact of 2000–2050 climate change on fine particulate matter (PM2. 5) air quality inferred from a multi-model analysis of meteorological modes. Atmospheric Chemistry and Physics Discussions, 12, 18107-18131. doi:10.5194/acpd-12-18107-2012

"Our multi-model ensemble analysis [for 2000-2050] allows us to conclude with greater confidence that changes in synoptic circulation brought about by climate change will degrade PM2.5 [fine particulate matter] air quality in the Eastern US but that the effect will be small (~0.1 μgm^{-3})."

Tai, A. P., Mickley, L. J., & Jacob, D. J. (2010). Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. Atmospheric Environment, 44(32), 3976-3984. doi:10.1016/j.atmosenv.2010.06.060

"Increased stagnation in the future climate would cause a corresponding increase in PM2.5 [fine particulate matter] levels, as shown in Fig. 6. GCMs [general circulation models] consistently find more frequent and prolonged stagnation episodes at northern mid-latitudes in the future climate (Mickley et al., 2004; Murazaki and Hess, 2006; Wu et al., 2008). Leibensperger et al. (2008) found for the East in summer a strong anticorrelation between the number of stagnant days and the frequency of mid-latitudes cyclones. They pointed out that midlatitude cyclone frequency has been decreasing over the 1980-2006 period and attributed this trend to greenhouse warming. Extrapolating their 1980-2006 trend in summer cyclone frequency (-0.15 a_1) to 2050, and using their observed anticorrelation between cyclone frequency and stagnant days, would imply 4.5 more stagnant days per summer in the East by 2050. From our results in Fig. 6, this translates to an average increase of 0.24 mg m_3 in summer mean PM2.5 concentrations with a maximum increase of 0.93 mg m_3 in the Midwest."